



REVIEW OF POSSIBLE WASTE HEAT SOURCES FROM INDUSTRIAL FACILITIES AND THEIR POTENTIAL USE

János DÓSA

University of Petroșani, Faculty of Mechanical and Electrical Engineering, Department of Mechanical, Industrial Engineering and Transportation, Petroșani, Romania. iondosa@upet.ro

Abstract

The aim of the paper was to review the main reusable sources of heat from industrial facilities and to analyze the most efficient way in which they can be exploited. In order to carry out some case studies, examples were chosen from fields of industry in which energy consumption is very high, namely the energy and mining industries. It was shown that although there are large amounts of energy that can be recovered, they are generally low temperature heat sources. Their efficient recovery can be achieved with the help of heat pumps, but due to the final temperature of the heat source, which is around 70 °C, they can be used mainly as heat sources for heating or hot water. This use greatly limits the research and projects for the reuse of these secondary energy resources, therefore future research should focus on obtaining higher temperatures, but also on the production of steam from these sources. The production of steam would facilitate an increase in projects for the recovery of these secondary energy resources for industrial use, which would lead to a superior valorization of them.

Keywords: waste heat, secondary energy resources, heat recovery, primary energy source savings.

1. Introduction

The guideline drawn by the EU from a sustainable development point of view is concretized by the European Green Deal which stated that we are striving to be the first climate-neutral continent.

The starting point of the strategy is that climate change and environmental degradation are an existential threat to Europe and the world. To overcome these challenges, the European Green Deal will transform the EU into a modern, resource-efficient and competitive economy. The major goals of the Green Deal can be summarized as follows: no net emissions of greenhouse gases by 2050; economic growth decoupled from resource use; no person and no community left behind.

An important part of the action plan is a set of proposals to make the EU's climate, energy, transport and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels.

It is also not accidental that two of the featured initiatives are energy related: REPowerEU and EU action to address energy crisis.

Basically, this is the mainframe in which Europe's industry will be functioning in the future.

2. Industry and power demand

The current state of the European Union from an energy point of view will be analyzed in the following section.

In [figure 1 \[1\]](#) can be seen that the primary energy consumption of the EU, compared to 2005, dropped. Also, the impact of the COVID pandemic can be clearly noticed.

Another important aspect is that the use of hard coal and brown coal dropped consistently, and as a result, in order to meet the energy demand use of natural gas, petroleum and nuclear energy grew. The overall tendency is the decrease of the primary energy consumption.

The gross electricity production as presented in [figure 2](#) highlights that fossil fuels were again the leading source for electricity generation. The second source is nuclear, but hydro power and green energy is also in the top.

From a heat recovery point of view in order to show the current state of the use of renewable resources, data presented in [figure 3](#) are important.

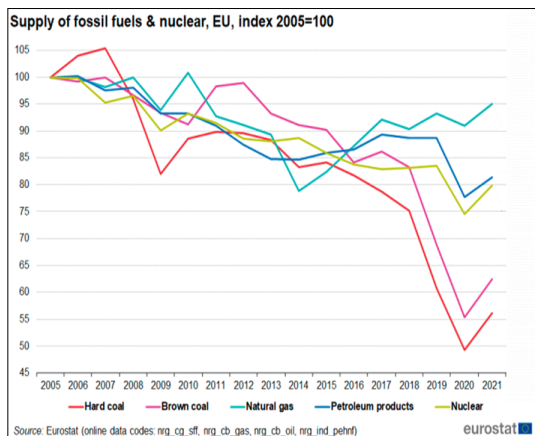


Figure 1. Primary energy supply. [1]

Renewables inland consumption (calculated) in the EU

	2017	2018	2019	2020	2021
TJ Geothermal	283 521	284 082	288 813	288 822	284 292
TJ Solar thermal	190 137	179 916	194 823	187 583	190 553
TJ Ambient heat (heat pumps)	456 113	486 381	520 765	553 193	630 597
TJ Biogases	581 985	580 288	592 251	614 908	625 835
kt Biogasoline	3 839	4 118	4 356	4 339	4 811
kt Biodiesels	12 951	14 532	14 731	15 072	15 718
kt Bio jet kerosene	0	0	0	0	0
kt Other liquid biofuels	1 350	1 382	1 499	1 484	1 362
TJ Primary solid biofuels	3 869 241	3 984 029	4 057 549	4 025 668	4 359 881
kt Charcoal	517	528	500	444	437
TJ Renewable municipal waste	397 656	390 913	395 136	399 661	409 465
TJ Non-renewable municipal waste	393 219	386 537	390 248	395 068	399 305
TJ Industrial waste (non-renewable)	185 722	195 742	202 075	206 295	207 573

Source: Eurostat (online data code: nrg_cb_rw)

Figure 3. Renewables inland consumption. [1]

Gross electricity production in the EU, GWh

	2017	2018	2019	2020	2021
Anthracite	4 103	4 013	680	715	636
Coking coal	11 164	8 805	13	81	64
Other bituminous coal	316 143	286 535	205 613	154 218	190 144
Sub-bituminous coal	3 170	2 394	1 554	572	389
Lignite	301 921	291 618	241 259	195 292	226 128
Brown coal briquettes	2 329	2 132	1 799	1 510	1 663
Coke oven gas	7 770	7 204	7 166	6 237	6 117
Gas works gas	1 939	1 803	1 734	1 250	142
Blast furnace gas	20 844	20 866	19 455	16 343	20 053
Peat	5 243	5 922	5 161	3 137	2 502
Oil shale and oil sands	9 912	9 380	4 318	2 247	3 444
Natural gas	525 178	490 689	569 312	560 997	551 784
Refinery gas	6 550	7 158	6 955	6 622	6 310
Liquefied petroleum gases	452	237	232	147	145
Gas oil and diesel oil	10 518	9 704	10 274	10 087	10 461
Fuel oil	28 737	25 614	24 894	21 345	23 388
Petroleum coke	2 280	1 577	621	517	465
Solid biofuels	74 261	76 252	80 560	82 959	92 752
Biogases	55 648	55 096	54 991	55 766	52 603
Industrial waste (non-renewable)	2 750	2 925	2 942	2 639	2 573
Renewable municipal waste	18 739	19 335	19 011	18 873	19 573
Non-renewable municipal waste	18 218	18 838	18 584	18 334	18 797
Hydro	322 463	370 234	345 643	375 487	374 849
Pure hydro power	281 813	326 819	306 478	331 709	330 758
Mixed hydro power	22 720	27 044	23 276	25 838	27 915
Mixed hydro power - pumping	10 187	9 981	9 494	10 367	10 355
Pumped hydro power	17 931	16 372	15 889	17 940	16 177
Geothermal	6 715	6 655	6 726	6 717	6 538
Wind	312 313	320 616	367 118	397 799	386 866
Solar thermal	5 883	4 867	5 683	4 992	5 176
Solar photovoltaic	102 052	108 200	118 202	140 125	158 588
Tide, wave, ocean	522	480	499	509	503
Nuclear	759 383	761 943	765 338	683 512	731 701
Heat from chemical sources	1 172	1 099	1 038	1 089	1 105
Other fuels (including non-specified)	22 551	20 860	19 848	19 560	16 081
Total (excluding pumped hydro)	2 932 807	2 916 698	2 881 840	2 761 371	2 885 010

Source: Eurostat (online data codes: nrg_ind_pehrl, nrg_ind_pehnl)

Figure 2. Gross electricity production. [1]

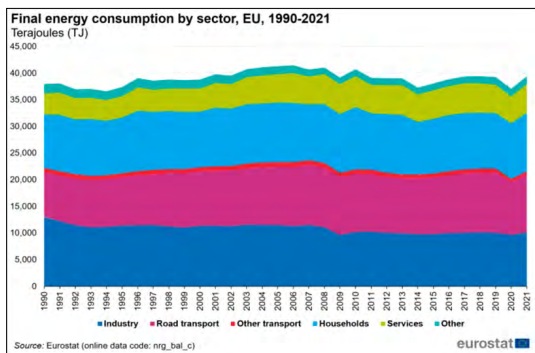


Figure 4. Final energy consumption by sector. [2]

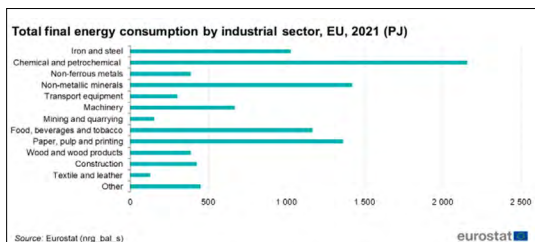


Figure 5. Final energy consumption by sector. [3]

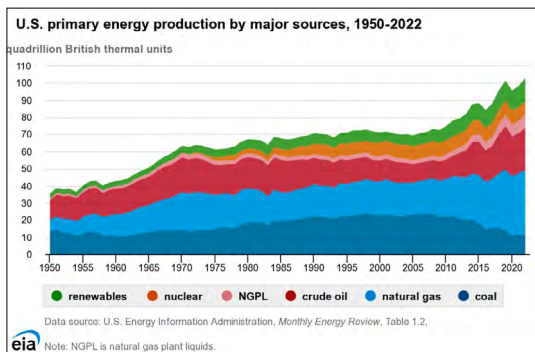


Figure 6. Primary energy consumption U.S. [4]

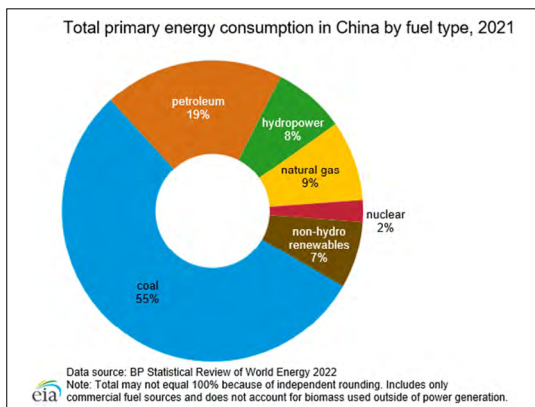


Figure 7. Primary energy consumption China. [5]

In the first place is the primary solid biofuel consumption followed by biogases.

Is important to notice that use of heat pumps also has an important share that is increasing over time. Renewable and non-renewable municipal waste, as well as non-renewable industrial waste have their share, but there is room for improvement.

Regarding the use of final energy, figure 4 shows that there are three major energy consumers: industry, road transport and households.

While heat recovery in road transport can be technically challenging, and the large share of household is due to their large number (which makes heat recovery usually economically inefficient), it means that from energy recovery point of view we should focus on industry.

The Energy-Intensive Industries cover a broad range of sectors such as chemicals, steel, paper, plastics, mining, extraction and quarrying, refineries, cement, wood, rubber, non-ferrous metals, glass and ceramics.

Their share in the final energy consumption is presented in figure 5 mutatja be [3].

Some discussions must take place regarding the data presented in figure 5, as the numbers are absolute values, and they must be analyzed from energy-intensity point of view. Therefore, the share of a certain industry in the overall consumption will be analyzed.

For example, the mining industry is far more energy-intensive than can be inferred on the basis of figure 5.

Its current status is due to the fact that the mining industry in Europe almost no longer exists as a result of the closure of most of the mines.

In order to have a complete picture, data on energy production and consumption in the case of the USA and China will be presented.

Figure 6. ábrát shows that ,compared to figure 1, the data are almost the same. In figure 7 the large share of coal in the primary energy consumption of China cannot be overlooked.

A more complex picture is presented in figure 8 [6], regarding energy consumption by source and sector in the case of the USA.

Data in figure 8 is consistent with data in figure 4 as major end user sectors are transportation, industry and residential (household).

Comparing data in figure 5 with data in figure 9 reveals that in China the share of the mining industry in total energy consumption is greater than in the case of EU (figure 5). and in recent

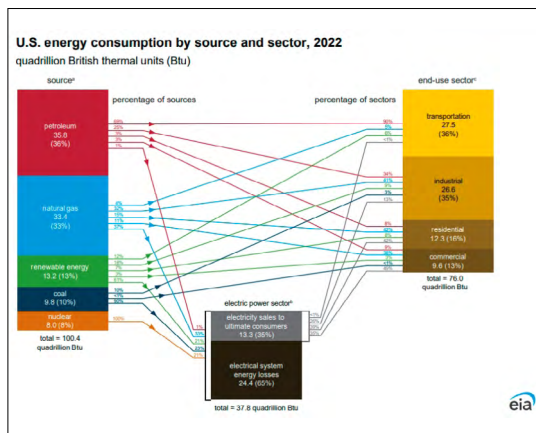


Figure 8. Energy consumption by source and sector. [6]

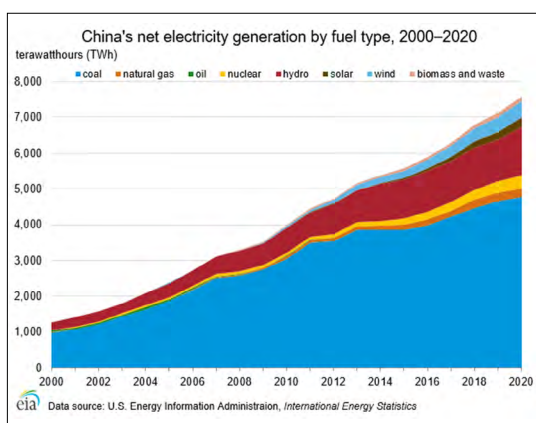


Figure 9. Net electricity generation by fuel type (China). [5]

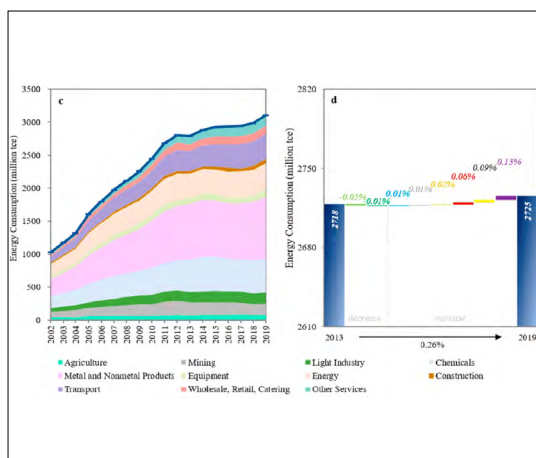


Figure 10. Energy consumption by industry sector (China) [7]

years this energy consumption is quite constant as China still has its mining industry.

Moreover, energy consumption in the mining industry is on the third place, which shows that mining is an energy-intensive industry.

Another important aspect is that in figure 10 the energy industry is also presented as major consumer, being in the first place in terms of share of total energy consumption. In case of the EU and the USA the share of energy industry is not listed.

Conclusively due to the weight of industrial consumption as presented above, and within it the share of the energy and mining industry, in the following, recoverable heat sources within them will be identified and evaluated from the magnitude and efficiency of recovery point of view..

3. Waste heat sources in industry

Waste heat recovery is not a new topic, and consequently such heat sources have already been mapped out [8].

A short enumeration will be helpful in the process of discovering the most promising recoverable heat source from heat recovery point of view.

Some of the most typical waste heat sources and their potential for energy recovery are [8]:

- process exhaust air (flue gas) between 30% to 90% can be utilized;
- waste heat from cooling systems - between 35% to 95% can be utilized as process heating supply;
- air compression facilities – up to 90% of electrical capacity can be recovered;
- ventilation technology – 35% to 90% can be utilized for fresh air preheating.

3.1. Waste heat in energy industry

The waste heat sources enumerated above can be found in all industrial sectors.

As stated above, the energy sector and mining industry were chosen in order to evaluate possibilities of waste heat recovery.

In order to highlight the very high potential of the industrial waste heat from a heat recovery point of view two types of waste heat sources were considered:

- waste heat from cooling systems;
- waste heat from air compression.

3.1.1. Amount of waste heat from condenser cooling

There are many studies in literature regarding the operation of a thermal power plant. The amount of heat released into the environment by

condenser cooling is 66 % according to Gajendra [9] while according to Kale in [10] the loss is 34 %. In other works, heat rejected by the condenser was found to be between 39,11 % to 42,87 % [11], and 45,02 % to 45,98 % [12] depending on power plant load.

These figures are high, and in absolute values are around 200 MW for data listed in [11] [12].

Assessment of the available heat that can be recovered from condenser cooling waste heat can be made using data gathered during heat balance calculations.

In figure 11 the schematic of a 200 MW thermal power plant is presented.

The steam turbine that works within this power plant is a condensing type turbine and was designed to operate at 3,000 rpm, 13 MPa pressure, and 545 °C temperature with one steam reheat to a temperature of 545 °C at a pressure of 2.44 MPa. The exhaust pressure of steam is 0.0034 MPa. The turbine has seven bleeder connections for regenerative feed water heating. Maximum temperature of feed water is 242 °C. From the outlet of the High Pressure Turbine (HPT) steam is directed to the re-heater at a pressure of 2.89 MPa and 350 °C. Steam is returned to the Reheat Turbine (RT) having a higher temperature. The Low Pressure Turbine (LPT) is of a double-flow design.

Steam for the turbine is provided by Pp-330/140-P55 type steam generator, a once-through coal-fired boiler [13].

An energy audit was carried out for this power plant and, as regulations require for heat balance calculations, measurements were carried out for at least 3 different loads. The loads for performance tests were fixed to 460 t·h⁻¹ – 70%, 560 t·h⁻¹ – 85% and 640 t·h⁻¹ – 94% (steam flow rate).

Data in table 1 shows the huge amount of heat available as waste heat and rejected by the condenser in the environment.

In order to be able to choose the appropriate heat recovery method, besides the amount of available heat the temperature of heat source is also important.

In table 2 the cooling water temperatures are presented..

The subject of another case study will be analyzed: a 150 MW rated output power plant.

The schematic of this power plant is presented in figure 12.

This power plant is equipped with K 160-130-2PR-2 type steam turbine, presented in the schematic diagram of the 150 MW unit (figure 12) .

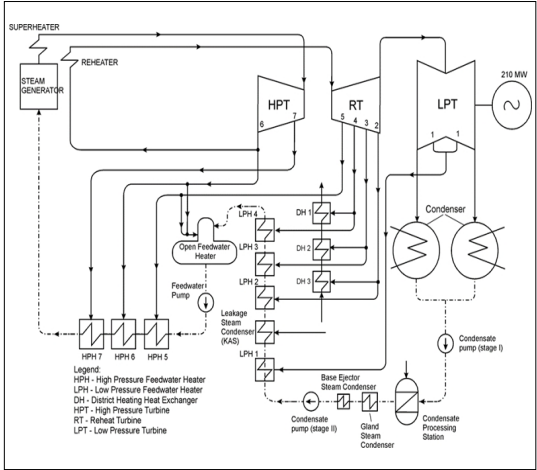


Figure 11. Schematic of the 200 MW power plant [11]

Table 1. Condenser loss

Load	Heat rejected by condenser Pcd, MW
70%	209.291
85%	259.989
94%	261.675
Average loss	243.652

Table 2. Cooling water temperatures

Load	Cooling water temperature at condenser inlet, °C	Cooling water temperature at condenser outlet, °C
70%	26.00	32.74
85%	27.93	36.43
94%	26.19	35.15

This turbine is a condensing type turbine with uncontrolled bleed, designed to operate at 12.8 MPa pressure, and 540 °C temperature, with one steam reheat to a temperature of 540 °C at a pressure of 3.41 MPa. The exhaust pressure is 0.0038 MPa. At the listed steam parameters and a cooling water temperature of 12 °C, the calculated power of the turbine can reach 170 MW.

It also can deliver up to 175 MW (150 Gcal·h⁻¹) of thermal energy from an unregulated bleeder at 150/70 °C or 130/70 °C in the district heating network.

Abbreviations used in figure 12 are: HPT – high pressure turbine; RT – reheat turbine; LPT – low pressure turbine; CP, CP-1, CP-2 – condensate

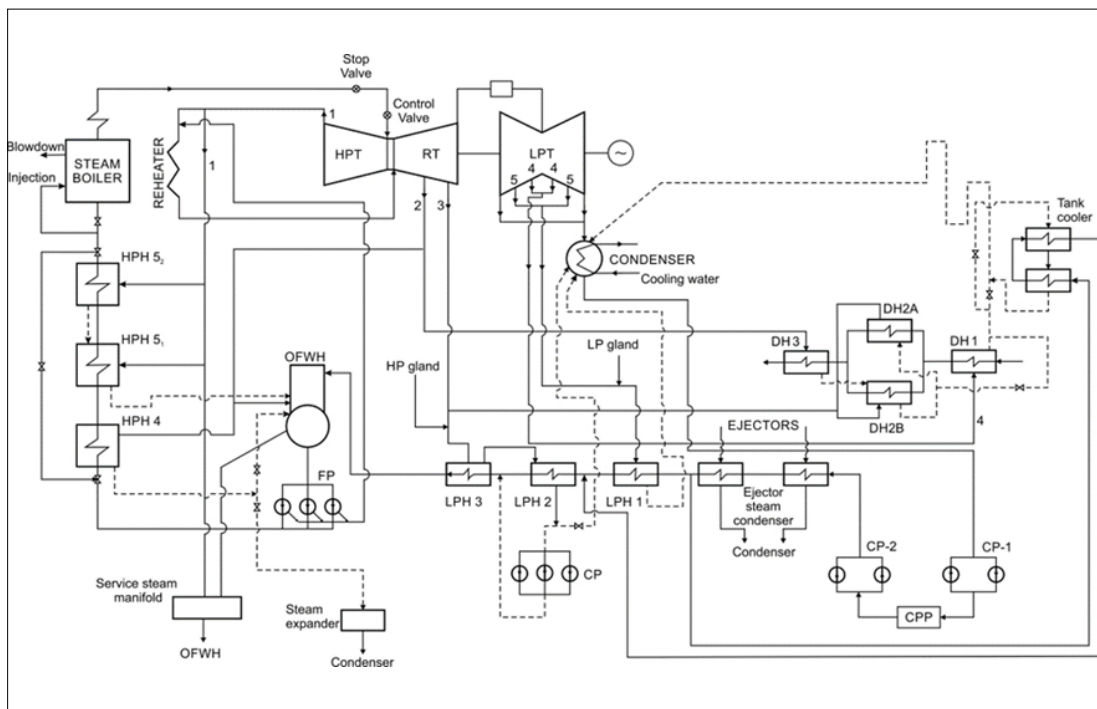


Figure 12. Schematic of 150 MW power plant. [12]

pumps; LPH – low pressure feedwater heater; HPH – high pressure feedwater heater; FP – feedwater pump; DH – district heating heat exchanger; CPP – condensate polishing plant.

The turbine has five bleeder connections for regenerative feed water heating to 235.4 °C. From the High-Pressure Turbine (HPT) steam enters the reheater at a pressure of 3.12 MPa and 350.7 °C temperature, from which it is returned to the Reheat Turbine (RT). The Low-Pressure Turbine (LPT) is of a double-flow design.

Steam for turbine is a coal-fired boiler, with 540 t·h⁻¹ rated steam output, at a pressure of 13.85 MPa and 541 °C for live steam and 471.4 t·h⁻¹ at 2.96 MPa and 541 °C temperature for reheat steam. Feed water parameters at steam generator rated load are: pressure 18.8 MPa, temperature 235.4 °C.

The loads for performance test, for this power plant, were fixed to 115 MW, 130 MW and 150 MW power output for condensation operation.

Data in [table 3](#) shows the amount of heat available as waste heat rejected by the condenser for the 150 MW power plant. The amount of heat is close to the value in [table 1](#).

The temperature of the cooling water for the 150 MW power plant is presented in [table 4](#).

Table 3. Condenser loss

Load, MW	Heat rejected by condenser P_{cd} , MW
115	185.380
130	216.480
150	262.759
Average loss	221.540

Table 4. Cooling water temperatures

Load	Cooling water temperature at condenser inlet, °C	Cooling water temperature at condenser outlet, °C
70%	19.2	30.84
85%	21.44	34.62
94%	24.69	40.32

3.1.2. Waste heat from turbocompressor cooling

Modern compressors employed today in the mining industry are rotary-screw compressors, but in the case of high air requirements and necessity of uninterrupted compressed air production, turbocompressors are also used. Choosing a

turbocompressor instead of a rotary-screw compressor is due to their high compressed air yields, and in addition, the turbocharger adapts well to the changing compressed air demand since the operating point of the turbocompressor moves, as for any such machine or pump, so no control is required if there is no major variation in the compressed air demand.

In the heyday of mining, the mines in Jiu Valley were all equipped with turbocompressors, and sometimes even up to three turbocompressors were in use.

This type of turbocompressor consists of seven stages, arranged in three bodies, the first two bodies having two rotors and the last having three. Cooling is performed by means of two intercoolers (Figure 13) and a final cooler, each of which is interchangeable.

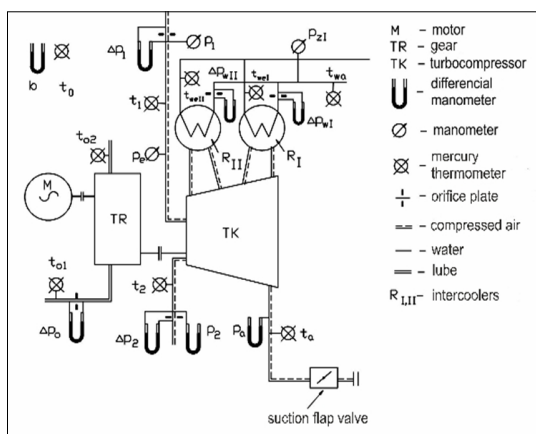


Figure 13. Schematic of the turbocompressor. [15]

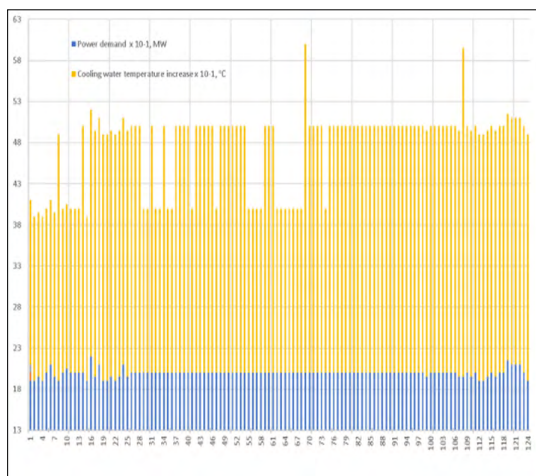


Figure 14. Measured data. [15]

Rated characteristics according to operation manual [14]:

Inlet air flow rate	16000 m ³ ·h ⁻¹ ;
Inlet pressure	1 bar
Inlet temperature	20 °C;
Outlet pressure	8 bar
Turbocompressor speed	9980 rpm;
Motor speed	1500 rpm
Air temperature at final cooler outlet	40 °C;
Cooling water temperature at inlet	25 °C;
Cooling water flow rates:	
– through final cooler	55 m ³ ·h ⁻¹ ;
– through intercoolers:	95 m ³ ·h ⁻¹ ;
– through oil cooler	20 m ³ ·h ⁻¹ ;
Rated motor power	1800 kW;
Motor efficiency	0.9;
Gear efficiency	0,95.

In order to accurately calculate the amount of waste heat, 124 measurements were made [15].

Measurement data is presented in figure 14.

Inlet temperature of the cooling water can vary from 15 °C in colder months (March), while in the summer months it can reach 28 °C. In winter even lower temperatures can be reached.

The temperature increase of cooling water is between 2-4 °C (2.75 °C average) and it is consistent with the motor power, which is directly proportional to the change in compressed air demand.

At a flow rate of the cooling water of 170 m³·h⁻¹ the inlet temperature was measured at the outlet of the cooling tower, while the outlet temperature of the cooling water was measured at the inlet of the cooling tower.

Therefore, amount of received heat is:

$$\begin{aligned}
 Q &= m \cdot c \cdot \Delta t = \rho \cdot V \cdot c \cdot \Delta t = \\
 &= \frac{997.05 \cdot 170 \cdot 4.186 \cdot 2.75}{3600} = \\
 &= 541,99 \text{ kW}
 \end{aligned} \quad (1)$$

where: Q – amount of heat, kW; V – volumetric flow rate, m³·h⁻¹; Δt – temperature difference, °C, c – specific heat capacity of water at 25 °C, kJ·kg⁻¹·K⁻¹, ρ – density of water, kg·m⁻³.

As can be seen, the amount of waste heat is very high, 542 kW, and all this is released into the environment. Not to mention that, high cooling water temperatures can lead to inadequate cooling of the turbocompressor, which negatively affects its efficiency. Another disadvantage resulting from inadequate cooling is that hot compressed air

raises the temperature in the quarry, which has a negative effect on humans.

Basically, if we solve the problem of waste heat recovery, we will be able to solve the problem of proper compressor cooling as well, and will be able to extract a desired amount of heat, assuring that way the proper cooling of the turbocompressor. Solving these problems can bring huge energy savings.

The biggest challenge in this case, in terms of waste heat usage, is that the temperature of the water is very low, so that it cannot be used as it is in other technological processes.

3. Efficiency of waste heat recovery

To better understand the amount of waste heat available, some calculation can be carried out.

Heat demand of an average household can be met usually by installing a 28-kW boiler for heating and hot water delivery.

Assuming that we can recover all the heat rejected by the condenser which theoretically is 221,540.0 kW we can provide heating for 7912 households, and if we consider recovering the heat from the turbocompressor cooling water, we can provide heat for 19 households.

Waste heat recovery can be conducted through various waste heat recovery technologies, but their applicability depends on the temperature of the source.

In examples listed above the temperature of the heat source is everywhere between 10 °C for winter time and as high as 40 °C in summer. That means that the waste heat is a low temperature heat source.

For low temperature heat sources, the mechanical vapor compression, water-water type [16] heat pumps (figure 15) are suitable for harnessing energy. They can use waste heat from water with temperatures under 40 °C, and deliver heat at temperatures between 50 to 80 °C with a COP (coefficient of performance) in the range of 2.5 – 5.0.

Usually, a heat pump extracts heat from a source, such as the surrounding air, geothermal energy stored in the ground, or nearby sources of water.

In order to evaluate the efficiency of heat recovery let's assume that we recover heat from the cooling water of condenser of the 150 MW power plant.

As hot water is usually delivered using pipelines, losses can occur, so we set the required heat delivery for the heat pump to $Q_i = 700$ kW, a value

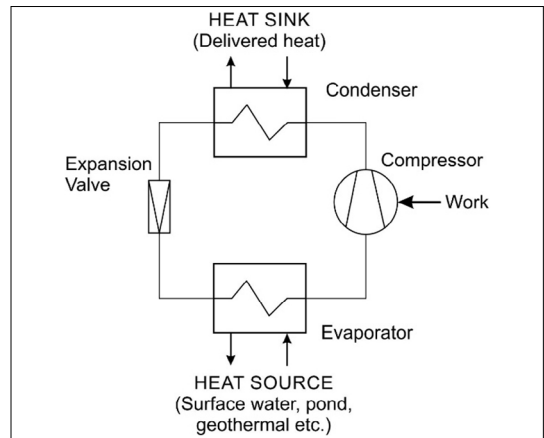


Figure 15. Vapour compression heat pump.

close to the maximum capacity of heat pumps employed today.

Additional data for calculation are: $T_i = 70$ °C – temperature of delivered hot water, $T_a = 5$ °C – ambient temperature, $\Delta T_c = 5$ °C – temperature difference required for heat transfer in condenser (heat delivery), $\Delta T_o = 5$ °C – temperature difference required for heat transfer in evaporator, $\Delta T_{sr} = 10$ °C – temperature difference for sub-cooling, mechanical efficiency $\neq 0.9$, employed refrigerant R717 (ammonia).

It must be stated that the ambient temperature will be the average temperature in the evaporator taking into account that at outlet of evaporator water temperature must be above 5 °C to prevent freezing, and the inlet temperature is the condenser outlet temperature. In order to compare the efficiency of using waste heat as heat source, a heat pump using the heat source a body of water is calculated first, considering heat source temperature 5 °C, this will represent a basis of comparison.

Data in table 4 regarding cooling water temperatures were measured during summer.

Results are presented in table 5 and figure 16.

In addition, primary energy resources savings brought by a heat pump can be calculated using equation [17]:

$$\Delta E = \left(1 - \frac{\eta_{CT}}{\mu_e \cdot \eta_{sis}} \right) 100, (\%) \quad (2)$$

where μ_e is the practical COP (coefficient of performance); $\eta_{sis} = 0.35$ – efficiency of electricity production in the national power grid; $\eta_{CT} = 0.85$ – energy efficiency of hot water production in heat-only boiler stations.

Table 5. Heat pump efficiency

Heat source temperature, °C	Work supplied to compressor P_e , kW	Practical COP μ_e	Exergy efficiency η_E
5	265.613	2.656	55,90
25	213.648	3.28	47,74
28	210.437	3.32	45,24
32.5	205.635	3.40	41,29

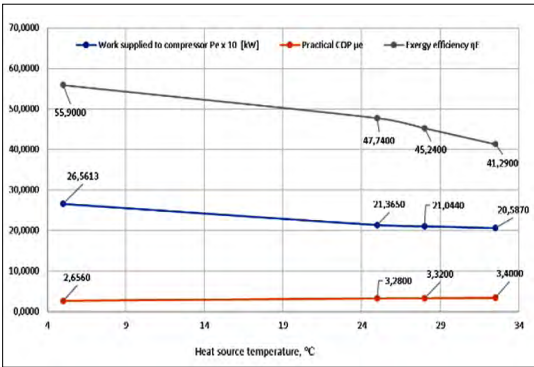


Figure 16. Work supplied, practical COP and exergy-efficiency of heat pump.

Data presented in **figure 16** reveals that the exergy efficiency of the heat pump varies from 55.90 to 41.29 % for the studied temperature range.

COP of the heat pump increases with the temperature of the heat source up to 3.40 while the work supplied to compressor decreases from 265.613 kW to 205.87 kW. The primary energy resources savings calculated with equation (2) varies from 8.56 % to 28.57 %.

Hot water can be produced locally by small boiler units with energy efficiencies around 85% or obtained from cogeneration plants having up to 80% energy efficiency.

In order to compare these values with exergy efficiency of heat pump, exergy efficiency of boiler units and cogeneration plants must be established. Literature provides data on cogeneration plants showing that exergy efficiency can vary from 23% to 30.7% [18][19], while exergy efficiency of boilers can be between 16% to 25% [20].

4. Conclusions

A great amount of waste heat is available in industry, as in the examples provided, it can be seen that the value of the heat rejected by the power plant condenser is 243.652 MW for the 200 MW power plant and 221.540 MW for the 150 MW

power plant. The heat that can be recovered from turbocompressor cooling is 542 kW.

A major problem linked to this waste heat is that it is a low temperature heat source.

Using heat pump technology in order to recover waste heat is a very good solution as the COP of heat pump is between 2.65 and 3.40, while the exergy efficiency is between 55.90 and 41.29 %.

Using heat pump technology can lead to important primary energy savings varying from 8.56 % to 28.57%, higher values for high heat source temperature.

Unfortunately, the temperature of delivered heat is around 70 °C, which limits its usage to heating or hot water supply. As industrial facilities are located usually far away from human settlements, heat needs to be delivered, and that can dramatically decrease the overall efficiency of recovery (depending on distance).

This shortcoming can be eliminated by creating industrial parks near these secondary heat resources.

Another solution could be that research should be developed in the direction of increasing the temperature of the recovered heat source (waste heat to steam solutions), increasing the possibility of using it in different directions, within the framework of industrial facilities.

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